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Dynamic forming limits and numerical optimization of combined quasi-static and impulse metal forming

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ABSTRACT

Subject of this work is the incorporation of forming limits in the numerical optimization of technological forming processes for sheet metal. Forming processes with non-linear load paths and strongly varying strain-rate, such as, e.g., combinations of deep drawing and electromagnetic forming are of particular interest. While in the latter impulse forming process inertial forces play a significant role, the first one is of quasi-static nature such that inertial forces may be neglected. Although classical forming limit diagrams provide an easily accessible method for the prediction of forming limits, they cannot be applied in situations involving pulsed loading along non-linear strain paths. Hence, they are extended to forming limit surfaces here. The target function to be minimized is computed via finite-element simulation. To avoid a large number of simulations, an interior point method is employed as optimization method. In this algorithm, forming limits appear via a logarithmic barrier function, which has to be computed sufficiently fast. The optimization algorithm is exemplarily applied to an identification problem for a two-stage forming process.

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1. Introduction

Virtual design of technological processes becomes an increasingly viable alternative to a purely experimentally based process layout. It decreases the number of experiments required, and hence, reduces time and costs. In many industrial areas, such as, e.g., the automotive industry [1], these methods are nowadays being employed. Product-Lifecycle-Management [2–4] can be considered as another example. There are several approaches to the computer based design of technological processes. In many cases expert systems store certified knowledge about the technological process to be identified in a database, which is applied to the given situation with the help of suitable logical rules. In this work, however, methods are considered that rely on mathematical optimization of a measurable quantity associated with the output of the technological process: Parameters of forming processes are identified such that a desired forming result is reached as close as possible. The target function to be minimized typically represents the deviation from a prescribed ideal value of a certain quantity computed for the proposed parameters, e.g., the distance of the computed shape of a deformed workpiece from the ideal shape, measured in the sense of error squares. As a single computation of the target function requires a complete simulation of the technological process to be optimized, e.g., by the finite element method, the number of its evaluations should be minimized as much as possible. This can be reached by employing optimization algorithms that are based on a descent in the parameter space computed via linearizations of the target function. To this end, an interior point (IP) method is utilized in this work.

A main goal of this work is the development of methods to implement constraints in the optimization algorithm guaranteeing that forming limits are never violated, while the parameter space is explored by the optimization method. In case of the IP-optimization method, these have to be implemented via so called logarithmic barriers. This, however, requires a fast accessible computational method to estimate the distance to the point of material failure at any stage of the currently active load path considering the current strain rate. There are two well known methods that allow for determination of this information: Use of a damage model with identified model parameters or of forming limit diagrams. The first alternative, on the one hand, is in most cases too time-consuming. Usually, a set of damage variables is introduced and their evolution is tracked by a system of Gauß-point-based ordinary differential equations to be solved any time the material model in the finite-element-simulation is evaluated. Such models are, e.g., the

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Gurson- or the Lemaitre-model. A classical forming limit diagram (FLD), on the other hand, is neither able to account for the material's load history during the forming process nor the dependence of the material's response on the strain rate. Hence, conventional FLDs are not suited to predict forming limits of combinations of deep drawing and electromagnetic forming.

To obtain a sufficiently fast method that can efficiently be incorporated in the IP-optimization method via logarithmic barrier functions and that accounts for strain history and strain rate dependence, the classical FLD is extended to a forming limit surface (FLS) in this work. To represent the relevant forming limits for a process combination of, e.g., a quasi-static and an impulse forming method, a third axis is added to a classical FLD. On this third axis, additional to major and minor strain a parameter is considered that may represent the accumulated strain in a critical region of the workpiece at the instant of switching from the quasi-static to the dynamical process. Then, for this parameter the forming limit curve corresponding to this amount of accumulated strain and the strain rate of the subsequent impulse forming operation is inserted.

The developed optimization method is finally applied to identify process parameters of a two-stage process combination of deep drawing and electromagnetic forming: At first certain parameters of this process combination are experimentally optimized. The resulting configuration is then used for validation of the finite element simulation of the process combination. Next, the IP-optimization algorithm is applied to identify process parameters best suited for a certain forming task. Finally, a geometrically slightly different process chain is numerically optimized for comparison.

To make the ideas of this article more coherent, a particular two-stage forming combination of deep drawing and a subsequent electromagnetic calibration step is introduced in Section 2, which shall give the reader a better understanding of the motivation of this work. This process combination will serve as an example for the general concept of using mathematical optimization for the identification of process parameters outlined in Section 3. The most important part is the incorporation of forming limits as constraints to the IP-optimization method presented in Section 4. The target function considered here will be evaluated with the help of a finite-element discretization of the whole process combination as shown in Section 5. In Section 6 results of a numerical optimization process are presented and compared to an experimentally based optimization. Additionally, a different geometrical situation is numerically investigated. The article ends with a discussion of future prospectives (Section 7) and some conclusions (Section 8).

2. Combining deep drawing and electromagnetic forming

To make the discussion more coherent, a particular combination of quasi-static deep drawing and electromagnetic impulse forming is now presented. This process combination involves non-linear strain-paths with varying strain-rate and is hence well suited both as motivation for this work and as a benchmark for a method to consider forming limits as constraints in mathematical optimization algorithms.

The underlying idea for studying this process combination is to extend the forming limits of a conventional forming method (here: deep drawing) by combining it with a high speed process (here: electromagnetic forming). Deep drawing is one of the most frequently utilized industrial forming methods. Usually it is driven by the pressure exerted on a metal sheet by a punch. Forming is guided by a die and the material's flow is controlled by the blank holder force, the radius of the drawing ring at the flange, the bottom radius of the punch, the geometrical details of the drawing ring, the punch, and the die, and finally the friction between the workpiece and the tool. In this setting, the material flow of the sheet metal results from stretch-compression loading, stretch-bending loading or a combination of both. In case of an axisymmetric workpiece drawn over a ring, the prevailing load is a combination of radial stretch and tangential compression [5]. It is well known that different forming paths occur in different parts of the domain of plastic flow during deep drawing. Consequently, the corresponding FLDs look different as has been demonstrated in [6–10]. During deep drawing, failure occurs both in form of necking or cracks. How good a prescribed ideal shape can be achieved before damage occurs depends on the parameters mentioned above. This can particularly be adjusted via the blank holder force. If for a given blank holder force the distance to a prescribed ideal shape shall be decreased more than the quasi-static forming limits admit or if additional details are to be produced, an electromagnetic forming step can be added. Such a process chain has first been proposed by Vohnout [11].

Electromagnetic forming is a high speed forming method in which strain rates over 1000 s^{-1} are achieved. Deformation of the workpiece is driven by the Lorentz force, a material body force that results from the interaction of a pulsed magnetic field with eddy currents induced in the workpiece by the magnetic field itself. The energy transferred by the Lorentz force is, however, not immediately transformed into plastic work. A great portion of it is first stored as kinetic energy in the workpiece, which then leads to deformation by inertial forces [12]. The magnetic field is generated by a tool coil adjacent to the workpiece, which is excited by the discharging current of a capacitor bank. In the situation considered in this work, the tool coil is integrated in the punch of the drawing press (see Fig. 1). Typically, a current of several 10,000 A is set up within a time comparable to 10 μs, leading to magnetic flux densities in the order of 1–10 T in the gap between tool coil and sheet metal. The whole forming process takes about 100 μs. As an individual forming process, EMF has already been scientifically studied in the 1960s, as described, e.g., by Daehn [13]. EMF possesses a huge potential to extend forming limits of classical techniques, particularly as part of a process chain [11]. In such a combination, all advantages of this forming method can take effect: Above all, an increased formability enables the extension of classical forming limits, as we will see below. Further, by a suitable design of the tool coil, loads can be applied very locally and, hence, the spectrum of applicable load distributions is enormously extended. Next, tool coils can often completely be integrated into other forming tools, such that fully integrated multi-stage process combinations become possible (see Fig. 1 as an example). Finally, the process only takes about 100 μs, such that the additional time required for a subsequent calibration step by electromagnetic forming can be neglected. For detailed information and recent results on

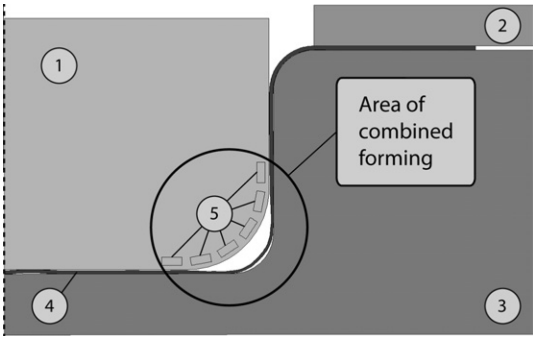

Fig. 1. Tools employed for the two-stage process chain consisting of a tool coil (5) for EM calibration placed in the punch (1). The coil is wound around the axis of symmetry (dashed line on the left), close to the bottom of the punch and close to its outer radius. The workpiece (4) is held down by a blank-holder (2) and formed into a die (3).

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